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Preceding Crop Affects Grain Cadmium and Zinc of Wheat Grown in Saline Soils of Central Iran

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ABSTRACT

Enhanced Cd concentrations in wheat (*Triticum aestivum* L.) grain produced on saline soils of central Iran have been recently reported. Because wheat bread is a major dietary component for the Iranian people, practical approaches to decrease Cd concentration in wheat grain were investigated. This study investigated the influence of sunflower–wheat vs. cotton–wheat rotations on extractable Cd and on Cd uptake by wheat in these salt-affected soils. Two fields with different levels of Cd contamination (1.5 and 3.2 mg total Cd kg^{-1} dry soil) were cropped with different rotations (cotton–wheat and sunflower–wheat) in Qom province, central Iran. Seeds of cotton (*Gossypium* L.) or sunflower (*Helianthus annuus* L. cv. Record) were planted in plots. After harvesting of the plants and removal of crop residues, wheat (cv. Rushan) was seeded in all plots. For both studied soils, the concentrations of Cd extracted by 0.04 *M* EDTA and 1 *M* $CaCl_2$ were significantly ($P \leq 0.05$) greater after cotton than after sunflower. Accordingly, the total amount of Cd in sunflower shoot was significantly ($P \leq 0.05$) greater than in the cotton shoot. Shoot Cd content in wheat plants grown after cotton and sunflower were significantly different; wheat shoots after cotton accumulated more Cd (two to four times) than after sunflower. Wheat grain Cd concentration after sunflower was much lower (more than seven times) than after cotton. The results of this study showed that sunflower in rotation with wheat in salt-affected soils of central Iran significantly reduced the risk of Cd transfer to wheat grain.

Trace element content of food has a large impact on human health. Deficiencies of Zn and Fe are widespread (Bouis, 2002; Welch, 2002), while excess accumulations of Cd may also occur (Chaney et al., 2004). Trace element concentration is of concern in staple foods such as cereals, which make up a large proportion of diet of Iranians.

High Cd of grains and food may cause proximal tubular dysfunction of the kidney after about 50 yr of consuming diets with high Cd levels (Nogawa et al., 1987). A limit of 0.2 mg kg^{-1} has been proposed as the maximum Cd level for cereal grains (CODEX Alimentarius Commission, 1999).

Applications of phosphorus (P) fertilizers that contained Cd as an impurity are largely responsible for the increasing Cd load in agricultural soils worldwide (McLaughlin and Singh, 1999). During the last 30 yr, large amounts of P fertilizers have been used in salt-affected soils of central Iran. Most of the applied P fertilizers contained very high ($<$300 mg kg^{-1}) concentrations of Cd. The Cd that has been applied with P fertilizer may well be plant available and adversely affect food quality. In countries where Cd in rice has caused kidney tubular dysfunction in human populations, wastes from Zn-Pb ore mining and smelting caused soil contamination of Zn and Cd. However, grains of rice have increased only in Cd concentration despite very high soil Zn contamination of the paddy fields (Chaney et al., 2004).

Saline soils represent over 30% of arable land in Iran (Khoshgoftar et al., 2004). The environmental implications of salinization in terms of uptake of Cd and Zn by crops have yet to be fully assessed (McLaughlin et al., 1997; Khoshgoftar et al., 2004). There is evidence of enhanced Cd uptake by some tested crop species, including cereal crops due to elevated salinity or chloride (Cl^-) concentrations (Bingham et al., 1984; McLaughlin et al., 1997; Smolders and McLaughlin, 1996; Norvell et al., 2000; Weggler et al., 2004). Under saline conditions, high Cl^- concentrations in the soil solution could increase the degree to which Cd is chloro-complexed (McLaughlin et al., 1994). Chloro-complexation raises total Cd concentrations in solution (Garcia-Miragaya and Page, 1976) and could enhance Cd uptake by crops through either faster Cd diffusion to roots or greater Cd uptake if chloro-complexes are transported across the root membrane (McLaughlin et al., 1997). Deficient Zn status also enhances Cd accumulation in wheat grain, and low Zn status interacts with high chloride to further increase grain Cd (Khoshgoftarmanesh et al., 2006). Enhanced Cd and reduced Zn concentrations in grain wheat cultivated in saline soils of central Iran have been recently reported (Khoshgoftarmanesh et al., 2006). As wheat bread is a major food for the Iranian people, some practical approaches to decrease Cd and increase Zn concentration in wheat grain need to be identified.

Cadmium accumulation in crops is influenced by crop genetics and Cd activity in the soil solution (Grant et al., 1999). Therefore, management practices may be used to reduce the level of Cd in the edible portion of crops (Grant et al., 1999; Mench, 1998).

Crop species differ widely in their ability to absorb, accumulate, and tolerate Cd (He and Singh, 1994; Grant et al., 1999; Chaney et al., 1999). Natural variation occurs in the uptake and distribution of Cd and Zn in crop species. Sensitive crops, which have high potential for transfer of Cd into the food chain, should be grown on soils which contain low levels of phytoavailable Cd (Grant et al., 1999).

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Abbreviations: AAS, atomic absorption spectrometry; GFAAS, graphite furnace atomic absorption spectrometry; NIST, National Institute of Standards and Technology; SWRI, Soil and Water Research Institute.

Sensitive crops grown in rotation after crops with high Cd residue may contain elevated Cd concentrations in the grain or seed of the sensitive crop (Grant et al., 1999). Long-term field experiments at separate locations indicated that Cd concentration in grain was highest in wheat grown after a legume such as lupins (*Lupinus albus* L.), field peas (*Pisum sativum* L.), or legume pasture, and lowest in wheat grown after another wheat, barley (*Hordeum vulgare* L.), or oats (Mench, 1998). Oliver et al. (1993) reported that the Cd concentrations in grain were highest in wheat grown after lupins and lowest in wheat grown after barley. The high Cd concentration in grain from lupins/wheat plots could not be explained by soil acidification (Oliver et al., 1993).

However, selecting plant species with greater ability for Cd uptake in their nonedible tissues in rotation with wheat may be an important approach to reduce the concentration of Cd in grain of wheat grown in contaminated soils. Sunflower (*Helianthus annuus* L.) and cotton (*Gossypium* L.) are two major crops planted in rotation with wheat in salt-affected soils of central Iran, but there is no information on the effect of these plants on the grain Cd concentration of wheat grown in rotation. Therefore, the objective of this study was to investigate the effect of sunflower and cotton cultivation on soil-extractable Cd and the Cd uptake by wheat grown in salt-affected soils.

MATERIALS AND METHODS

Field plot experiments were conducted in 2002 at two locations with different levels of Cd (site A: 1.5 and site B: 3.2 mg total Cd kg^{-1} dry soil) and two crop rotations (cotton–wheat and sunflower–wheat) in Qom province, central Iran. The mean annual temperature was 30°C. The total precipitation was about 109 mm. The soils were classified as Typic Calcigypsids (Soil Survey Staff, 1999). Cadmium accumulation in the soils of Qom province is attributed to high applications of P fertilizers that contain Cd as an impurity for many years. Cadmium accumulation, but not Zn accumulation, has been reported in these soils (Khoshgoftarmanesh et al., 2006).

In mid-March, surface (0 to 30 cm) soil samples from two sites (five subsamples) were collected, air-dried, and crushed to pass a 2-mm sieve. Soil pH (1:2 soil/water) was measured using a digital pH meter (Model 691, Metrohm AG Herisau Switzerland) (Thomas, 1996a) and electrical conductivity (EC_e) using an EC meter (Model Ohm-644, Metrohm AG Herisau Switzerland) (Rhoades, 1996). Organic matter content was determined by the Walkley and Black method (Nelson and Sommers, 1982). Percentages of clay were measured using the Hydrometer method (Gee and Bauder, 1986). The $CaCO_3$ equivalent was determined by neutralizing with HCl and back titration with NaOH (Black et al., 1965). Available P content was extracted from the soil with 0.5 *M* $NaHCO_3$ (Olsen and Sommers, 1982) and was determined by a colorimetric method (Black et al., 1965). Available K was extracted with ammonium acetate and determined on a flame photometer (Thomas, 1996b). DTPA-extractable Zn was measured as described by Lindsay and Norvell (1978). One hundred mg of air-dried soil subsamples were digested in a mixture of HNO_3–$HClO_4$–HF on a hot plate until the digest turned into a light yellowish sticky mass. A 10% HNO_3 solution was added to the digest until a volume of 10 mL was obtained for analysis of total Cd and Zn (Black et al., 1965) and then determined using graphite furnace atomic absorption spectrometry (GFAAS) (PerkinElmer 3400, PerkinElmer, Wellesley, MA) with deuterium background correction. Selected properties of these soils are shown in Table 1.

Both sites were chisel-plowed in October of 2001. Nitrogen and K fertilizers (160 kg ha^{-1} N and 80 kg ha^{-1} K as urea and K_2SO_4, respectively) were applied to each plot. The two sites were then cultivated by disk plow. The N and K fertilizer rates were determined by the Soil and Water Research Institute (SWRI) fertilizer recommendation method (Milani et al., 1998). Seeds of sunflower (cv. Record) or cotton were planted on 20 March in 21-m^2 plots. Row spacing was 0.75 m, and plant density was 8 per m^2. Herbicides were applied as needed to both plants. Ground waters from two different wells in the Qomroud region, which had EC of 3.2 (for site A) and 4.1 (for site B) dS m^{-1} were used for crop irrigation. At harvest, shoot yields were determined for each plot and the entire shoot biomass was removed from the plots. For analysis of Cd and Zn, shoots of each plant were separately cut at the soil surface, washed with deionized water, dried at 70°C, ground, dried for 48 h, ashed at 550°C for 8 h, and the ash dissolved in 2 *M* HCl (Chapman and Pratt, 1961), and Zn and Cd were determined by GFAAS.

In September, the plots that had previously been in sunflower or cotton were lightly disked before sown to winter wheat. Wheat (cv. Rushan) was seeded at 340 seeds m^{-2} in 18-cm rows in all plots on 23 October. Urea was broadcast at 150 kg urea ha^{-1} immediately before sowing the wheat.

After harvesting the wheat in May 2003, concentrations of Zn and Cd in the subsample of shoot and grain were determined by GFAAS with deuterium background correction.

Before sowing the wheat and after harvest, soil Cd concentrations were extracted using 0.04 *M* EDTA and 1 *M* $CaCl_2$ (Young et al., 2000). Calcium chloride extractions involved shaking 4.00 g soil with 20 mL solution, and EDTA extractions involved shaking 5.0 g soil with 20 mL solution for 24 h. After extraction, the suspensions were centrifuged at 10 000 rpm for 10 min and filtered through a Whatman 42 filter paper before analysis of Cd by GFAAS with deuterium background correction.

The accuracies of Cd and Zn analyses were controlled by analyzing certified standard materials and including blanks in digestion batches. Analysis of National Institute of Standards and Technology (NIST) soil standard (San Joaquin #2709; certified Cd concentration, 0.38 ± 0.01 and Zn 106 ± 3 μg g^{-1}) gave Cd and Zn concentrations of 0.35 ± 0.04 and 103 ± 4 μg g^{-1}, respectively. Recovery of Cd was 92% and Zn 94% for apple leaf standard (#1573A).

The experiment was set up in a completely randomized factorial design with three replicates. Results were analyzed using ANOVA procedures and means were separated using protected LSD at the $P \leq 0.05$ probability levels (SAS Institute, 1988).

Table 1. Initial soil characteristics at the studied sites.

Characteristic	Soil A	Soil B
pH (water)	7.6	7.2
EC_e (dS m^{-1})	7.8	8.1
Organic carbon (%)	0.68	0.74
Clay (%)	38	27
$CaCO_3$, equivalent (%)	19	17
Available P (mg kg^{-1})	12	11
Available K (mg kg^{-1})	295	285
DTPA Zn (mg kg^{-1})	0.84	0.90
Total Zn (mg kg^{-1})	25	38
Total Cd (mg kg^{-1})	1.5	3.2

RESULTS AND DISCUSSION

Soil Cadmium after Sunflower or Cotton

For both soils, the concentrations of Cd extracted by EDTA and 1 M $CaCl_2$ was significantly ($P \leq 0.05$) greater after cotton than after sunflower (Fig. 1). This was probably due to greater removal of Cd from the soils by sunflower than by cotton. Also, there was no significant difference in soil pH between sunflower-grown plots and cotton-grown plots (data not shown). Thus the changes in Cd availability with soil pH were not a problem. We were not able to determine how sunflower in rotation caused lower extractable-Cd in the soils.

Cadmium concentrations in the EDTA extract were significantly ($P \leq 0.05$) greater than in the $CaCl_2$ extractant (Fig. 1). The EDTA extractant has been used as a measure of the phytoavailable Cd in soils (Gray et al., 2003). EDTA is a strong chelator of Cd and is considered to act by chelating surface-bound and solubilizing moderately soluble Cd ions from the soil solid phase (Nakhone and Young, 1993; Stanhope et al., 2000; Gray et al., 2003). However, it has been recently demonstrated (Young et al., 2000; Gray et al., 2003) that the amount of Cd extracted with 1 M $CaCl_2$ correlated with the proportion of labile Cd estimated using isotopic dilution techniques. It was suggested that the chloride ion is a moderately strong complexing agent for Cd, whereas the calcium ion competes with Cd for sorption sites in soils (Gray et al., 2003). It has been suggested that EDTA and $CaCl_2$ solutions might be suitable for predicting the availability of soil Cd (Khoshgoftar and Parker, 2005).

The soils used in this experiment were different in Cd extracted by HNO_3 (total Cd), EDTA, and $CaCl_2$ (Fig. 1). A reason for the difference in extractable and total Cd appears related to P fertilizer applications and amounts of Zn fertilizers applied by the farmers. The soil of site B received much more P fertilizers during previous years.

Shoot Cadmium Content of Sunflower and Cotton

There were significant ($P \leq 0.05$) differences in dry matter yield (Fig. 2) and Cd concentration in shoots of cotton and sunflower (Fig. 3). Accordingly, the amount of Cd removed by the cotton and sunflower shoots was significantly ($P \leq 0.05$) different (Fig. 4). The total amount of Cd in sunflower shoots was about 1.5-fold more than in the cotton shoots. As there was no difference in the shoot biomass of cotton and sunflower (data not shown), greater Cd content in sunflower is probably due to the higher Cd uptake by roots of sunflower. This result is in accordance with the lower extractable soil Cd after sunflower than after cotton, indicating reduced quantity of soil available Cd pool by more Cd removal. Cadmium accumulation in sunflower is higher than many other crop species (Li et al., 1997; Chaney et al., 1999). As expected, shoot Cd contents of both plants in soil B were greater than soil A (Fig. 3).

Very low Cd concentrations measured in sunflower kernels indicated limited translocation of Cd to kernels (data not shown). It is probably due to high capacity of sunflower to retain Cd in the shoots and inhibiting its mobility to kernels. The considerable genetic variation in Cd accumulation in sunflower kernels may also explain the low kernel Cd levels found in this experiment compared with others (Li et al., 1997). Some crop genotypes accumulate much higher Cd than others (Khoshgoftarmanesh et al., 2006).

Grain Cadmium and Zinc Concentration of Wheat

Shoot Cd content in wheat plants grown after cotton and sunflower were significantly different and wheat plants after cotton tended to accumulate more Cd (2 to

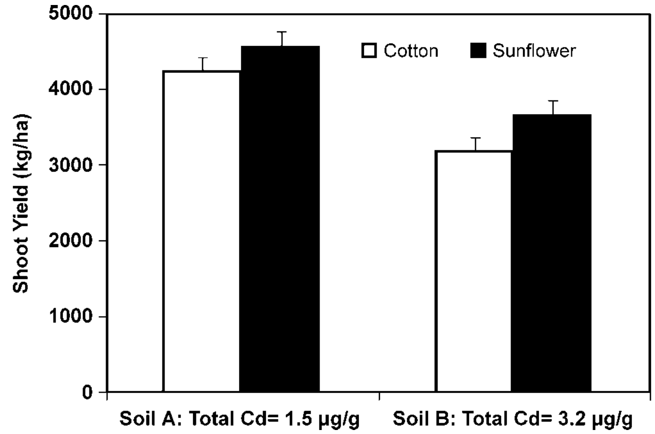

Fig. 2. Shoot dry matter yield of sunflower or cotton for two different Cd-contaminated soils. Error bars represent + SE (n = 3).

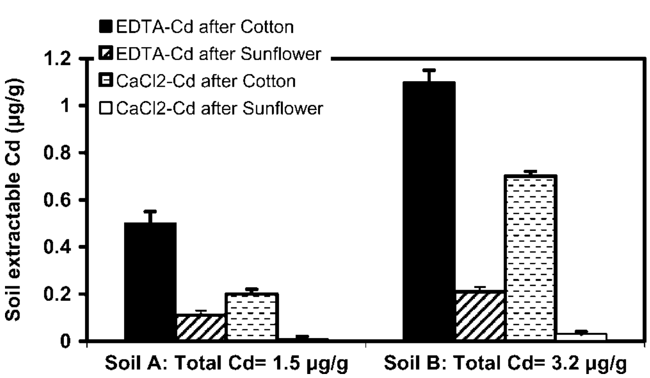

Fig. 1. Cadmium concentration in the EDTA and 1 M $CaCl_2$ extracts from soil after sunflower or cotton was grown. Error bars represent + SE (n = 3).

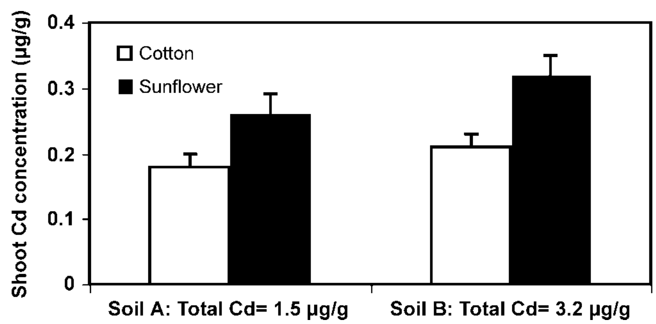

Fig. 3. Cadmium concentration in shoots of sunflower and cotton grown in two different Cd-contaminated soils. Error bars represent + SE (n = 3).

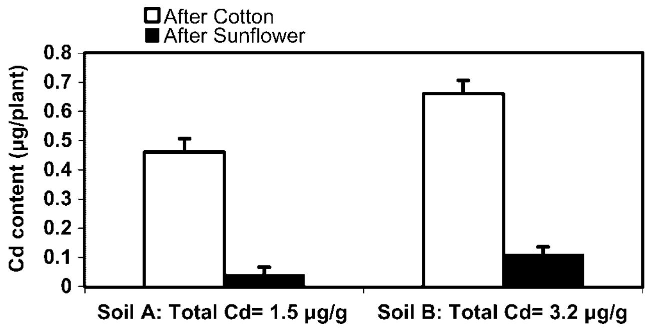

Fig. 4. Shoot Cd content in wheat grown after sunflower or cotton for two different Cd-contaminated soils. Error bars represent + SE (n = 3).

4 times) in their shoots (Fig. 4). Higher concentrations of soil-extractable Cd were found where cotton had been grown. In fact, sunflower could extract soil Cd greater than cotton and hence, less Cd existed in the soil solution for the roots of wheat plants to take up. Thus, grain Cd concentrations in wheat plants after sunflower were much less (about seven times) than after cotton (Fig. 5).

It has been indicated that crop rotation can be an important factor affecting Cd uptake. Under certain soil conditions (e.g., saline soils) and with wheat varieties that accumulate Cd, the Cd concentration in grain may exceed the maximum permissible concentration of 0.05 mg Cd kg^{-1} set by the Food Standards Australia New Zealand as a result of the crop rotation (Oliver et al., 1993). Grant et al. (1999) indicated the Cd concentrations in grain were highest in wheat grown after sunflower, where the previous crop residues were incorporated into the soil before planting wheat. Oliver et al. (1993) also reported that wheat following lupin had higher grain Cd than wheat after wheat or barley where the crop residue was not removed. The crop residue as it decomposed in the soil supplied more readily available Cd for plant uptake. In the present study, following the practice of local farmers, all the aboveground biomass that contained Cd was removed from the plot. Hence, the crop with higher Cd accumulation in the aboveground tissues reduced the risk of Cd transfer to the following wheat crop.

Wheat grown in soil at site B accumulated significantly higher Cd in their shoots than in plants grown in soil A. In contrast to Cd, grain Zn concentration in wheat plants grown after sunflower was significantly greater than after cotton (Fig. 6). This may be partly due

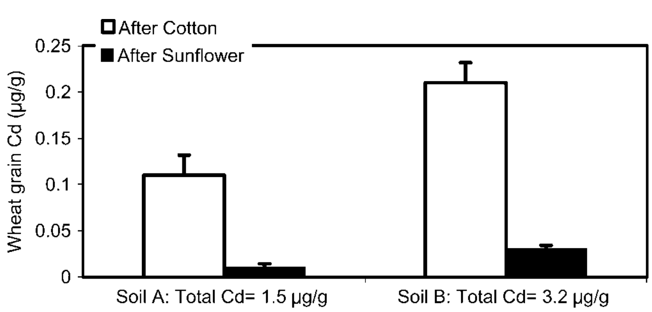

Fig. 5. Grain Cd concentrations in wheat plants grown after cotton or sunflower for two different Cd-contaminated soils. Error bars represent + SE (n = 3).

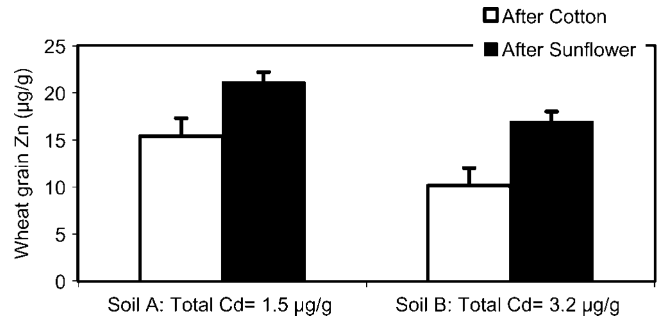

Fig. 6. Grain Zn concentrations in wheat plants grown after cotton or sunflower for two different Cd-contaminated soils. Error bars represent + SE (n = 3).

to lower soil Cd concentrations where sunflower was grown before wheat. Greater Cd concentrations in soil inhibits root Zn^{2+} uptake in wheat plants which could be attributed to competition for carriers of both Zn and Cd across root membrane (Homma and Hirata, 1984; Hart et al., 2002; Khoshgoftarmanesh et al., 2006). It has been reported that Zn^{2+} and Cd^{2+} inhibit the uptake of each other in the roots of wheat (Hart et al., 2002), although the affinity of the membrane transporter is different for both Zn and Cd. Membrane transporter affinity is greater for Cd than for Zn (Homma and Hirata, 1984; Hart et al., 2002), but soluble Zn is usually present at much higher concentration than is Cd in soil solutions (Khoshgoftar et al., 2004).

CONCLUSIONS

The results of this study showed that sunflower in rotation with wheat in Cd-contaminated salt-affected soils significantly reduced the risk of Cd transfer to wheat grain that is a main food for the Iranian people.

REFERENCES

Bingham, F.T., G. Sposito, and J.E. Strong. 1984. The effect of chloride on the availability of cadmium. J. Environ. Qual. 13:71–74.

Black, C.A., D.D. Evans, J.L. White, L.E. Ensminger, and F.E. Clark (ed.). 1965. Methods of soil analysis: Part 2. Agron. Monogr. 9. ASA, CSSA, and SSSA, Madison, WI.

Bouis, H.E. 2002. Plant breeding: A new tool for fighting micronutrient malnutrition. J. Nutr. 132(3):491S–494S.

Chaney, R.L., P.G. Reeves, J.A. Ryan, R.W. Simmons, R.M. Welch, and J.S. Angle. 2004. An improved understanding of soil Cd risk to humans and low cost methods to remediate soil Cd risks. BioMetals 17:549–553.

Chaney, R.L., J.A. Ryan, Y.-M. Li, and S.L. Brown. 1999. Soil cadmium as a threat to human health. p. 219–256. *In* M.J. McLaughlin and B.R. Singh (ed.) Cadmium in soils and plants. Kluwer Academic Publ., Dordrecht, The Netherlands.

Chapman, H.D., and P.F. Pratt. 1961. Methods of analysis for soils, plants and waters. Univ. of California, Div. of Agric. Sci., Riverside, CA.

CODEX Alimentarius Commission. 1999. Report of the 33rd session of the codex committee of food additives and contaminants. ALINORM 99/12. FAO, Rome, Italy.

Garcia-Miragaya, J., and A.L. Page. 1976. Influence of ionic strength and inorganic complex formation on the sorption of trace amounts of Cd by montmorillonite. Soil Sci. Soc. Am. J. 40:658–663.

Gee, G.W., and J.W. Bauder. 1986. Particle-size analysis. p. 383–409. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA, CSSA, and SSSA, Madison, WI.

Grant, C.A., L.D. Bailey, M.J. McLaughlin, and B.R. Singh. 1999. Management factors which influence cadmium concentrations in crops: A review. p. 151–198. *In* M.J. McLaughlin and B.R. Singh (ed.) Cadmium in soils and plants. Kluwer Academic Publ., Dordrecht.

Gray, C.W., R.G. McLaren, and J. Shiowatana. 2003. The determination of labile cadmium in some biosolids-amended soils by isotope dilution plasma mass spectrometry. Aust. J. Soil Res. 41:589–597.

Hart, J.J., R.M. Welch, W.A. Norvell, and L.V. Kochian. 2002. Transport interactions between cadmium and zinc in roots of bread and durum wheat seedlings. Physiol. Plant. 116:73–78.

He, Q.B., and B.R. Singh. 1994. Crop uptake of Cd from phosphate fertilizers: I. Yield and Cd content. Water Air Soil Pollut. 74:251–265.

Homma, Y., and H. Hirata. 1984. Kinetics of cadmium and zinc absorption by rice seedling roots. Soil Sci. Plant Nutr. 30:527–532.

Khoshgoftar, A.H., and D.R. Parker. 2005. Salinity changes the extractability of Cd in the soil and its concentration in wheat. 8th Int. Conf. of the Biochemistry of Trace Elements (ICOBTE), April 2005, Adelaide, Australia.

Khoshgoftar, A.H., H. Shariatmadari, N. Karimian, M. Kalbasi, S.E.A.T.M. van der Zee, and D.R. Parker. 2004. Salinity and Zn application effects on phytoavailability of Cd and Zn. Soil Sci. Soc. Am. J. 68:1885–1889.

Khoshgoftarmanesh, A.H., H. Shariatmadari, N. Karimian, and S.E.A.T.M. van der Zee. 2006. Cadmium and zinc in saline soil solutions and their concentrations in wheat. Soil Sci. Soc. Am. J. 70:582–588.

Li, Y.-M., R.L. Chaney, A.A. Schneiter, J.F. Miller, E.M. Elias, and J.J. Hammond. 1997. Screening for low grain cadmium phenotypes in sunflower, durum wheat, and flax. Euphytica 94:23–30.

Lindsay, W.L., and W.A. Norvell. 1978. Development of a DTPA soil test for zinc, iron, manganese, and copper. Soil Sci. Soc. Am. J. 42:421–428.

McLaughlin, M.J., L.T. Palmer, K.G. Tiller, T.A. Beech, and M.K. Smart. 1994. Increased soil salinity causes elevated cadmium concentrations in field-grown potato tubers. J. Environ. Qual. 23: 1013–1018.

McLaughlin, M.J., and B.R. Singh. 1999. Cadmium in soils and plants. Kluwer Academic Publ., Dordrecht, The Netherlands.

McLaughlin, M.J., K.G. Tiller, and M.K. Smart. 1997. Speciation of cadmium in soil solutions of saline/sodic soils and relationships with cadmium concentrations in potato tubers (*Solanum tuberosum L.*). Aust. J. Soil Res. 35:183–198.

Mench, M.J. 1998. Cadmium availability to plants in relation to major long-term changes in agronomy systems. Agric. Ecosyst. Environ. 67:175–187.

Milani, P.M., M.J. Malakouti, Z. Khademi, M.R. Balalim, and M. Mashayekhi. 1998. A fertilizer recommendation model for the wheat field of Iran. Soil and Water Research Institute, Tehran, Iran.

Nakhone, L.N., and S.D. Young. 1993. The significance of (radio)labile cadmium pools in soil. Environ. Pollut. 82:73–77.

Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. p. 539–579. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. Agron. Monogr. 9. ASA, CSSA, and SSSA, Madison, WI.

Nogawa, K., R. Honda, T. Kido, I. Tsuritani, and Y. Yamada. 1987. Limits to protect people eating cadmium in rice, based on epidemiological studies. Trace Subst. Environ. Health 21:431–439.

Norvell, W.A., J. Wu, D.G. Hopkins, and R.M. Welch. 2000. Association of cadmium in durum wheat grain with soil chloride and chelate-extractable soil cadmium. Soil Sci. Soc. Am. J. 64:2162–2168.

Oliver, D.P., J.E. Schultz, K.G. Tiller, and R.H. Merry. 1993. The effect of crop rotations and tillage practices on cadmium concentrations in wheat grain. Aust. J. Agric. Res. 44:1221–1234.

Olsen, S.R., and L.E. Sommers. 1982. Phosphorus. p. 403–431. *In* A.L. Page (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA, CSSA, and SSSA, Madison, WI.

Rhoades, J.D. 1996. Salinity: Electrical conductivity and total dissolved solids. p. 417–435. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. Agron. Monogr. 9. ASA, CSSA, and SSSA, Madison, WI.

SAS Institute. 1988. SAS/STAT user's guide, release 6.03. SAS Inst., Cary, NC.

Smolders, E., and M.J. McLaughlin. 1996. Chloride increases cadmium uptake in Swiss chard in a resin-buffered nutrient solution. Soil Sci. Soc. Am. J. 60:1443–1447.

Soil Survey Staff. 1999. Soil Taxonomy. A basic system of soil classification for making and interpreting soil surveys. USDA Agriculture Handbook No. 436. U.S. Gov. Print. Office, Washington, DC.

Stanhope, K.G., S.D. Young, J.J. Hutchinson, and R. Kamath. 2000. Use of isotopic dilution techniques to assess the metabolisation of nonlabile Cd by chelating agents in phytoremediation. Environ. Sci. Technol. 34:4123–4127.

Thomas, G.W. 1996a. Soil pH and soil acidity. p. 475–490. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. Agron. Monogr. 9. ASA, CSSA, and SSSA, Madison, WI.

Thomas, G.W. 1996b. Exchangable cations. p. 159–165. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. Agron. Monogr. 9. ASA, CSSA, and SSSA, Madison, WI.

Weggler, K., M.J. McLaughlin, and R.D. Graham. 2004. Effect of chloride in soil solution on the plant availability of biosolid-borne cadmium. J. Environ. Qual. 33:496–504.

Welch, R.M. 2002. The impact of mineral nutrients in food crops on global human health. Plant Soil 247:83–90.

Young, S.D., A. Tye, A. Carstensen, I. Resende, and N. Crout. 2000. Methods for determining labile cadmium and zinc in soil. Eur. J. Soil Sci. 51:129–136.